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Approaching the Fault Passage Indicator

故障指示器综

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Abstract - **Fault Passage Indicators have been under development for the last 70 years, including new capabilities to satisfy the needs of the Distribution Network Operators. The traditional field of usefulness of such devices is assisting the fault location procedure, improving the power quality indices and reducing the associated costs. Recently, new capabilities are being added to these devices, such as monitoring, grid operation assessment, and topology reconfiguration, becoming more and more intelligent devices. Moreover, the massive expansion of the Fault Passage Indicator has led to develop directional fault detection methods without voltage sensors with the aim of reducing the installation costs, the tuning of the parameters and the simplicity of its operation. The paper gives an overview of the different advances of the technology and poses some of the challenges that this technology still needs to solve.**

Keywords – **Fault Passage Indicator, Reliability**

摘要 –故障指示器在过去七十年的发展历程中，一直在增加新的功能来满足配电网运营商的需求。它的传统作用集中在协助故障位置流程，提高电源质量指标和压缩相应成本上。近年例如监测、网络运行评估和重新设置电网拓扑等新的功能开发出来后，这类型仪器变得越来越智能。由于故障指示器的大规模发展，不依靠电压传感器的直接故障诊断方法被设计出来，降低了安装成本，简化了参数调整和运行。这篇文章总结故障指示器各种优势的同时也提出了这项技术仍需解决的问题。

关键词 – 故障通道指示器，可靠性。

I. Introduction

The concept of the Fault Passage Indicator (FPI) or Faulted Circuit Indicator (FCI) is nearly 70 years old. In its simplest form, the FPI indicates the flow of a high fault current through a grid conductor. In the past, generation units were not connected to the Distribution Network, but to the High Voltage (HV) transmission grid. This fact, together with the radial operation of the Medium Voltage (MV) Distribution Network, despite some meshed topologies, such as ring, led to a unidirectional current flow: from the main grid to the customers. Therefore, when a fault occurred under these conditions, a high current flowed from the grid to the fault point and this was the only possible direction. By detecting the fault over-current, it was simultaneously assumed that the fault was downstream of the FPI. The fault location crew or the linemen could track the different FPIs installed in the grid and finally reach the faulted cable section. The fault would be located between the last tripped FPI and the first not-tripped FPI.

In general terms, once the cable section is located, a precise fault localization is still required, with more accurate methods and equipment that points out the exact distance to the fault. Then, the faulted component can be repaired or replaced. In total, restoring an outage can take several hours, or even days, depending on the component and how easy is to repair or replace [1].

In its conventional version, the FPI is a device mounted on the conductor (line or cable) that measures the phase current. Strictly speaking, instead of measuring the current, the FPIs measure the magnetic field around the conductor. For overhead lines, the FPI hangs on the conductor between two poles, where the FPI mechanical support is also part of the sensor [2]. In underground cables, the FPI surrounds the conductor and the insulation (without the shield [3]) and is allocated mostly in the MV/LV substation. The device itself contains the sensor, the processing circuitry, the indication means and a system to power the device. Therefore, the FPI are designed to be compact and easy to install.

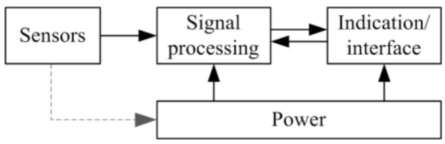


Fig.1, Simplified bloc-scheme of a Fault Passage Indicator

In low-impedance grounding grids (including solid grounding), both poly-phase and phase-to-ground faults provoke a large over-current, and, therefore, one FPI on each conductor is enough to detect all types of faults. In high-impedance grounding grids (isolated, resonant, etc.), phase-to-ground faults do not provoke large over-currents, and, therefore they may require a fourth FPI that senses and detects the homopolar current, called "sensitive earth fault detection". The fault type can be identified by checking which FPIs tripped.

A. Operation of the FPI

Setting up the FPI: Before starting the operation, the FPI requires some settings for fault detection: mostly over-current threshold and detection time.

Reading the FPI indication: The FPI normally includes a visual indication of the fault (a LED, a flag, etc.). A particular indication system is a glass bulb filled with liquid and a red pigment [4]. When the fault is detected, a metal ball in the bulb moves due to the strong magnetic field associated with a large current,, shaking the pigment and coloring the liquid. In the case of underground cable FPIs, the fault location crew needs to get into the substation to check the status of the indication, whereas in overhead lines, the crew needs to track the path of the overhead lines. It was found through experience that getting inside the substation to check the FPI indication was a time consuming task. In urban, highly populated areas it can be difficult to access the substations, or sometimes, the substation is allocated in a private property, so that permission of the owner is required. For this reason, alternative systems to obtain the FPI indication have been developed, such as acoustic "beep", audible from outside the substation, with the corresponding disturbance to the surrounding inhabitants. Another system is to connect an extra light indicator outside the substation, visible without getting inside [5]. The FPIs incorporated the ability of communicating via radio frequency with a SCADA system more than 30 years ago [6], however, SCADA systems have not been widely used in the lower MV distribution level. In a later stage, other communication systems have been used, such as Short Message Service (SMS), e-mail [7], power line communications (PLC), in combination with a Remote Terminal Unit (RTU). Amongst many possibilities, the use of communication has allowed the operator to know the faulted cable section almost immediately after the outage takes place.

Resetting the FPI: Once the FPI has tripped, the indication must remain on till the locating crew has checked the state, but afterwards, when the fault is cleared and the service is restored, the FPI has to return back to the normal state (off or not tripped), so that the device is able to indicate future faults. Non-reset FPIs would mislead the crew to the actual fault location, hence increasing the outage time. Moreover, it has been reported that the linemen may distrust any indication from these non-resetting devices [8].

The consequences of non-resetting the FPI may lead to important costs, related to the misleading of the crew. The practical implementation with analog electronic circuitry is done by means of a Set-Reset bistable, which allows the indication to remain on until a reset signal is sent [9]. This reset signal can be given by different means, or a combination of multiple ones:

1. Manual reset

This is the earliest and most simple type. Manual reset is possible when the circuit is energized, however, a hotstick or a magnet [8] may be required in those cases, amongst other tools. Manual reset FPIs are sensitive to some grid phenomena such as cold load pick-up, inrush currents, switching surges and so on [10], that, despite not being faults, can trip the FPI, remaining tripped without purpose. For that reason, mechanisms have been developed to avoid false tripping. For instance a time restraint, that delays the FPI operation over a few cycles, till the inrush current or the surge have passed [11], and then proceed with the normal detection method. Despite the simplicity of the manual reset, today FPIs are built with that option, since it acts as a back-up method for other, more sophisticated reset mechanisms. It appears evident that there is a need for an automatic reset method that does not require the crew to perform an operation on all the tripped FPIs.

2. Remote reset

Considering the availability of communications, the reset of the FPIs can be done remotely from the control center, once the fault is notified to be cleared. Hence, this method is analog to the manual reset, but executed from the control center.

3. Timed reset

The first reset mechanisms without crew intervention are those where the indication turns off after a pre-defined time. This has been done by means of mechanical methods (recall the FPI with red pigment particles that settle down after several hours), or electronically, by means of counters. This option is frequently offered by manufacturers and customizable by the DNOs. [12].

4. Measurement-based reset

During the outage, the electrical supply was interrupted, but afterwards, when the fault is finally repaired, the service is restored. By then, the tripped FPIs should be back to normal operation. Consequently, this sequence of operations leads to a reset mechanism based on current and/or voltage presence detection, above a threshold, that is interpreted as the restoration of the power supply.

It should be noticed that in many grids, mainly those with overhead lines, the circuit breaker at the beginning of the feeder is equipped with a recloser that follows a sequence of opening-closing maneuvers when a fault is detected. The objective is to avoid the *permanent* trip of the circuit breaker after self-extinguishing or transient faults that may self-de-energize after few cycles. By following an opening / closing /(opening) sequence, it can be confirmed whether the fault was transient or permanent. Hence, a simple detecting the presence of voltage or current is not enough to ensure that the service was already restored; it could just be a re-closing step of the above-mentioned sequence. The adopted solution to distinguish between the sequence step and the definitive restoration is often a timer that waits a time after the current and/or the voltage are detected [13]. This leads to complex logical schemes of actuation, because multiple counters have to interact before the indication is definitively tripped. Two main methods based on restoration detection have been proposed:

a) Voltage reset

Herein, the reset mechanism is based on electrostatic field detection (voltage presence). An advantage of voltage reset FPI types is that they do not depend on variable load conditions. The voltage reset mechanism has been divided into high- and low-voltage methods, depending on the place where the voltage is measured [8]. If the voltage is measured at the MV side (high-voltage type), the reset will happen after exceeding a threshold, normally of 5 kV. On the contrary, if the voltage is measured on the LV side of the transformer, the reset will occur when the transformer is energized again after the fault. The voltage presence can be measured either by precise voltage sensors, or by test points with a capacitive coupling to the energized conductor. The test points are not meant for measurement purposes, but for safety reasons, indicating live conductors. Moreover, in underground cables, they require the cable to be unshielded and a separable connector installed [14-15], unless the point is provided as part of the switch gear. A drawback of the low-voltage reset is reported in [8], where a fault happens in the transformer and the primary side fuse opens immediately. The transformer de-energizes and therefore the tripped FPI that sees the fault current cannot reset, despite the fact that the MV cable is still sound. Neglecting directionality issues, for the moment, the case and associated grid situation is described in Fig. 2.

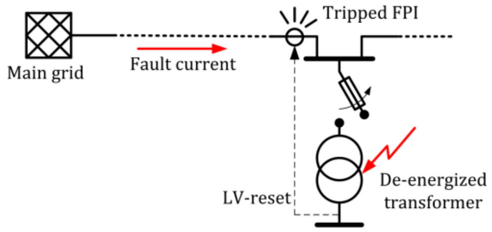


Fig 2, LV-reset issue, interpretation according to [8]

In the situation described above, the FPI may be allocated in the ingoing path of the MV/LV substation, so that is able to see the transformer fault. But in general terms, this implies that the FPI will detect those faults that occur either in the MV bus-bar or in the cable sections beyond. Hence, the application of this reset mechanism is dependent on the FPI allocation, within the context of the MV/LV substation. DNOs can choose whether to allocate the FPIs in the ingoing path to the transformer, the outgoing path, or both. Installing FPIs in both paths of the transformer increases the reliability, since the system is able to differentiate between cable section faults and MV bus-bar faults. Furthermore, in case of changing the grid topology, this statement remains valid.

Consider a loop feeder as shown in Fig. 3. The standard [10] recommends to install the FPIs in the outgoing path of the transformer, since cable faults are much more prevalent than bus-bar faults. For instance, the FPI of Tr1 would still see a bus-bar fault in Tr2. However, independently of the voltage reset choice, high or low voltage, it would still be able to reset after service restoration. Consider still the same figure. The loop feeder has an open point between Tr4 and Tr5. When allocating FPIs, it could be decided not to install FPIs, neither in Tr4 nor Tr5. However, one of the advantages of loop feeders is the possibility of reconfiguring the topology, so, beyond the faulted and isolated section, the substations can still be fed from the other side. In the case of grid re-configuration, the FPIs of the respective reconfigured and transferred substations would be positioned in the opposite direction as designed: now they are sensing the ingoing path, therefore there is the possibility of finding the scenario outlined in Fig. 2.

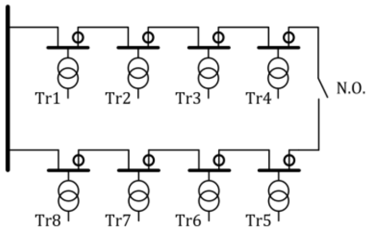


Fig 3, Loop feeder with normally open point

a) Current reset

Another method of resetting the FPIs is by sensing normal load current after restoration. This reset type is sensitive to the load current, and therefore manufacturers specify the minimum current to be sensed in order to reset, which is typically between 3 and 5A. Furthermore, decisions based on current measurements can be affected by the previous described phenomenon of the proximity effect [3]: the FPI on one conductor detects partially the magnetic field of adjacent conductors. Moreover, after the fault and the reconfiguration maneuvers, the load currents change and they may not be large enough to make the FPI reset. Consider the previous feeder topology, before a fault between Tr2 and Tr3 occurs, as in Fig. 4.

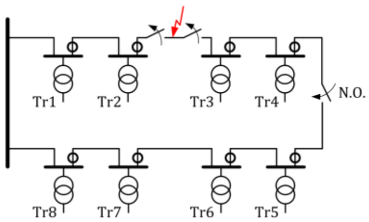


Fig 4, Loop feeder with fault and reconfigured topology

The fault is isolated and the normally open circuit breaker is now closed. Consequently, Tr3 and Tr4 are now fed from the other side (coming from Tr5) and the FPIs at Tr3 and Tr4 are now operating in reverse direction (recall that Tr4 was optional). Furthermore, before the fault happened, the FPI of Tr3 used to see the load current of Tr4, whereas after the fault, it sees only the load current of Tr3. Depending on the load currents and the reset current thresholds, it is possible that Tr3 does not reset.

Powering the FPI: The typical system to power the FPI is by means of a long life Lithium battery. Some non-rechargeable models are also available [16]. Another system to power the device is by harvesting energy from the monitored conductor. This system requires a minimum flowing current of about 3 to 5 A. In order to prevent the device switching off during valley periods, where the current is not high enough, FPIs using this system are often equipped with a small rechargeable battery.

The massive deployment of the FPIs has led to the definition of standards with recommendations for their application, mostly in residential grids, but also for testing them:

- IEEE 1216-2000: Guide for the Application of Faulted Circuit Indicators for 200 A, Single-Phase Underground Residential Distribution (URD) [17]

- IEEE 1610-2007: Guide for the Application of Faulted Circuit Indicators for 200/600A, Three-phase Underground Distribution [10]
- IEEE 495-2007: Guide for Testing Faulted Circuit Indicators [18]

II. GRID RELIABILITY

Despite the simplicity of the concept, it has proven to be a cost-effective solution to increase reliability. Many studies have related the deployment of the FPI technology with the outage duration reliability indices, such as System Average Interruption Duration Index (SAIDI) and Customer Average Interruption Duration Index (CAIDI), or the corresponding national indexes [19-21]. In order to illustrate how FPIs improve the grid reliability, it is necessary to compare their application with alternative fault location methods.

A. Alternative fault location methods

In case that FPIs are not installed, there are other ways of locating the fault that can back-up or eventually replace the usage of FPIs.

The first method relies on distance relays that compute the distance from the relay position to the fault location [22]. Fault distance computation algorithms have been successfully integrated at the transmission level. However, their performance in distribution grids is limited. First, because the distribution grids are often highly heterogeneous regarding the conductor types [23], which limits the accuracy of the relay. Second, because of the presence of laterals that the relay cannot effectively distinguish [24]. Moreover, despite some experimental studies [25], there are no distance relays to locate phase-to-ground faults in isolated neutral grids. In the rest of the cases, where the use of distance relays is possible, the use of FPIs is highly recommended to overcome the problem of the laterals [22].

Another method consists of trial-and-error circuit breaker maneuvers, where the faulted feeder is sequentially split in subsections, that are opened and re-closed in such a way that, after each maneuver, the faulted cable section is better defined and isolated [26]. Because of the successive re-closing maneuvers, it stresses the grid components, which are subject to high inrush currents. The voltage stress is of special importance in the component insulation during phase to ground faults in isolated neutral grids, where the healthy phases can be subject to phase voltages up to 1,8 times the phase nominal voltage [27]. When the fault is located via this method, it is possible to encounter the so-called *reclosing over fault*, where the circuit breaker recloses over an existing, permanent fault. Given that the grid is often not fully automated, the presence of a patrolling crew is required to perform the maneuvers. Some of them can remotely be controlled via communication and automated switches.

A hybrid approach can be adopted, so that few FPIs are installed in the grid, but the trial-and-error maneuvering approach is still performed for a more precise fault localization. In this case, FPIs are exposed to a potential operation problem. On one hand, FPIs need to withstand such reclosing maneuvers while still keeping the correct indication. On the other hand, FPIs must distinguish between high inrush and fault currents. Such inrush currents can be found when re-connecting the grid supply and large transformer magnetization currents appear.

Another back-up fault location method is the visual inspection of the conductors while patrolling along the feeder path. This method is a time consuming task, it is not suitable for underground cables, but it is doable if the overhead conductor path is alike to the street path. Despite these drawbacks, this technique is used as a back-up method by the DSO.

B. The business case of grid reliability and the FPIs

In [21], it is estimated a SAIDI reduction between 25-50% after installing FPIs in the grid. However, FPIs barely help to improve other indicators related to the frequency of faults directly, although in [19], it suggested to use the frequency of FPI indications to identify problem areas in the grid and apply preventive maintenance.

Given the comparative benefits of installing FPIs, many authors have built a business case around this technology considering the Energy Not-Served (ENS) by the DNO to the customers during the outage as the main economic driver [28]. The energy not delivered during the outage is not billed and, therefore, it is computed as an economic loss for the DNO at the residential kWh price. In [21], the load is estimated as 4 kW/customer/hour. Applying the same business case in other locations require adjusting the load estimation and the energy price. A general remark on such business case is the fact that a significant percentage of the energy not consumed during the outage is deferred until the supply is restored [1].

Once a fault happens, depending on the location in the grid, it can happen that a group of substations becomes non restorable because there is no alternative path of supply. Thereby, these substations shall remain unsupplied during the total outage duration. On the contrary, the other substations, restorable, can be supplied from another path. Therefore, the outage length business case should make a distinction between the restorable- and non-restorable-substations. The first type is sensitive only to the fault location time. On one hand, this has motivated the study of the optimal grid re-configuration topology after fault location and isolation. On the other hand, this motivates the construction of grid topologies such as rings or petals that offer a double feeding path in the most populated areas, where a single outage could potentially affect a significant number of consumers. Towards the automation of the distribution grid in combination with intelligence techniques, self-healing grids are those able to change their topology in order to overcome the problem of non-supplied substation once an outage happens [29]. The combination of these fields and techniques has led to the concept of FLISR (Fault Location, Isolation and Service Restoration), where the FPI has a great potential. In those geographically dispersed areas where a ring topology is not possible, the number of non-restorable substations will be significantly higher [30].

In the cited business cases, the impact of a power outage in the industry and business sectors is neglected, with the possibility of incurring production costs [31]. The reliability indexes are monitored at a national level [32-34] and the activities of the DNOs may be regulated to enforce national requirements. Through such regulations, DNOs are incentivized to invest and upgrade the grid assets, while they may also penalize DNO according to the obtained reliability indexes. In any case, building the business case in terms of ENS has allowed us to identify several bottlenecks in FPI performance that will be addressed in section IV.

IV. Improvements From the Business Case

A significant reduction of the outage time can be achieved with a limited amount of FPIs [20][35]. This has led to the treatment of the influence of FPIs on the abovementioned reliability indexes as an optimization problem, formulated in terms of minimizing the reliability indexes using the least FPIs as possible [36]. This approach requires a particular case study for each grid topology and, being an optimization problem, needs to be solved using diverse mathematical tools, such as genetic algorithms and evolutionary computing [37], fuzzy logic [38] or immune algorithms [39] amongst many other. In semi-urban and rural areas, an outage may not influence the reliability indexes as much as in urban, highly populated areas, hence, such optimization techniques may advise a partial coverage of the grid with FPIs. In this case, a combination of fault location methodologies may be required.

A. Optimizing the installation cost

In [40] it is estimated that the time to install a conventional FPI (sensor included) is between 1 minute and 1 hour. In most of the cases, such conventional FPIs do not include voltage sensors, which would significantly increase the installation time. During the installation operation, the supply must be switched off for safety reasons. In order to minimize this interruption time, several solutions have been proposed.

For overhead lines, two ways of sensing the over-current are used to date: The first solution consists of sensing the magnetic field of each conductor, thus at least 3 FPIs are required in total. Physically, each FPI is attached to one conductor, in Fig. 5. For that reason, in case of a faulted phase, only the FPI attached to that conductor will sense a high magnetic field. The fault type can be identified by checking which FPIs tripped. The exceptions are those cases where the fault current does not significantly increase, such as phase-to-ground faults in isolated or compensated neutral grids.

Fig. 5, FPI hanging around an air conductor. (left) [41]; (right) [42].

The magnetic field around the conductor, according to Faraday's law is:

$$B = \frac{\mu_0 I}{2\pi r} \tag{1}$$

Where μ_0 is the vacuum permeability, $4\pi\times10^{-7}$ H/m $\approx$ 1.25664×10^{-6} H/m, I is the current flowing through the conductor and r is the radius or distance to the conductor. The magnetic field crossing an area A provokes a magnetic flux Φ according to:

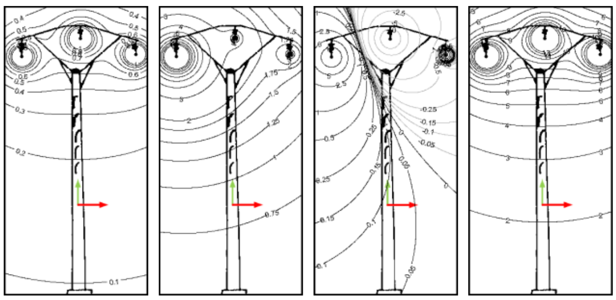
$$\Phi = BA\cos\theta \tag{2}$$

Where θ is the angle between the normal area-vector A and the magnetic field direction. The variation of the flux due to the AC-current induces an emf in the terminals of a coil of N turns, according to Lenz's law; $d\Phi/dt$ is the variation of flux over time:

$$\varepsilon = -N\frac{\partial\Phi}{\partial t} \tag{3}$$

Another solution requires only 2 sensors, attached to the pole, at low-medium height. One sensor is allocated to measure the horizontal magnetic field and the other sensor, the vertical field. In this case, the sensors are allocated far from the conductors, and consequently, the measured field is weaker. The manufacturers specify that the horizontal sensor is used to detect phase-to-ground faults, whereas the vertical sensor detects phase-to-phase faults. However, three-phase faults can also be detected with the horizontal sensor. With this solution, the faulted conductors cannot be identified. Furthermore, this system depends partially on the pole geometry and is sensitive to external influence. A commercial FPI using this sensing system is shown in [43].

Fig. 6 shows an approximation of the magnetic field created by the three air conductors hanging on a pole, under different current values. The magnetic field lines are overlaid on the pole geometry, so the difference between both systems can be appreciated. Note that (1) the closer the sensor is to the conductor, the stronger the sensed magnetic field and (2) under normal operation, phase-to-ground and three-phase faults, the predominant sensed current is in the horizontal direction, whereas for phase-to-phase faults, the field is mostly vertical. The plotted numerical values are only for qualitative analysis. This FPI type can be equipped with an electric field sensor, so that is partially able to provide directionality, using the classic voltage polarization principle.



(a) (b) (c) (d)

Fig. 6, Simulated magnetic field around overhead lines during different conditions. (a): Normal operation. (b): Phase-to-ground fault. (c): Phase-to-phase fault. (d): Three-phase fault. The FPI would be allocated approximately as high as the origin of the arrows, own source.

Other solutions to ease the installation of FPI in overhead lines imply using hot-sticks and FPI mechanical embodiments that can be solidly and irreversibly attached to the conductor, as in [2]. In the case of underground cables, the installation of some FPI types can require some processing of the cable, and this implies disconnecting the power supply during the installation time. Towards the reduction of this time, some solutions are available in the market. One solution consists of integrating the sensors in the elbow connector of the cable with the MV/LV substation [44-45]. Another solution consists of a set of magnetic field sensors becoming a chain that can be closed around a bundle of 3 cables, thus a single FPI for the three phases, as in Fig. 7.

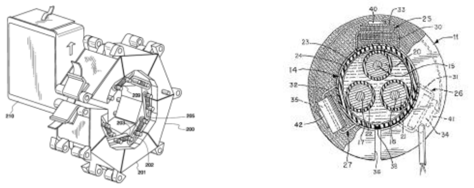


Fig. 7, FPI for cable bundles [9] (left) and sheathed cables [46] (right)

B. Communications

In section I, the use of communication for indication and reset purposes was mentioned. Besides the convenience of remotely reading the indication, a significant outage time reduction can be achieved, as reported in [28]. Nowadays, most of the commercial FPIs provide communications for that purpose. In [30], it was reported that the communication channel can fail and two alternatives are considered: (i) secure the reliability of the communication channel by means of specific contracts with communication suppliers, (ii) develop intelligent algorithms that can detect missing FPI indications and still determine the faulted region.

C. Grid monitoring

For quite some time, DNOs are increasingly concerned about the observability of the distribution network. While the High Voltage (HV) is highly monitored and fully equipped, the MV grid is barely monitored downstream of the feeder protective relays. Fig. 1 shows how the FPI is equipped with a current sensor (at least), which can sometimes be used for monitoring purposes. In this sense, FPIs are also equipped with data memory, so that they can store the measured values, calculate averages and so on. Thus, FPI integrated with a SCADA system can aid the grid operation.

D. Need for directionality

Since few years, more and more Distributed Generation (DG) is being connected to the distribution networks, both in the Low-Voltage and the Medium-Voltage grids. Besides the associated benefits, this connection introduces problems with fault location to the DNOs and their grids. The traditional approach to this technology was using non-directional FPIs, which were not equipped to distinguish the direction of the current flow, nor to indicate it. When connecting DG in the grid, in principle, these units are also able to inject current to the fault, independently of the feedpoint. Obviously, this implies that the performance of the old, conventional FPIs is compromised and they can trip both for forward (downstream) and reverse (upstream) directions, making it impossible to correctly determine the faulted feeder section from their readings. If that happens, the reliability improvement achieved in the past can be ruined. Several solutions have been proposed to tackle this problem. One of the solutions is the directional FPI that can distinguish the current flow direction. Following the approach of optimizing the amount of FPIs, DNOs may consider the selective replacement of non-directional FPIs by directional ones only in the strictly necessary case. This approach has been studied in [47]. Given the rapid implementation of directional FPI in the grid, this will be further detailed in section V, together with their fault detection capabilities.

V. Directional FPIs and Fault Detection

The directionality of the fault has been traditionally tackled with directional relays, which are of common use in HV transmission lines, and, up to some extent, in the protection of some MV feeders. The underlying concept is the polarization, which consists of calculating the angle difference between the polarizing and the operating magnitude [48]. Because of its high reliability, traditionally, the polarizing magnitude is a voltage and the operating magnitude is a current. This polarization principle can be found in many forms: as phase voltage vs phase current, positive-, negative-, zero-sequence voltage vs current, or a mix between phase magnitudes and symmetrical component magnitudes [48-50]. The most typical polarization modes are shown next in Table I (quadrature polarization) and Table II (sequence polarization).

TABLE 1, Quadrature Polarization (90°)

Operating quantity	Polarizing quantity
I_A	$V_{POL,A} = V_{BC}$
I_B	$V_{POL,B} = V_{CA}$
I_C	$V_{POL,C} = V_{AB}$

The current flow direction is determined by the sign of the "torque" (nomenclature inherited from the traditional, electro-mechanical directional relays) of Eq. (4). Positive torque sign indicates a forward fault, whereas negative sign indicates reverse current flow.

$$\begin{aligned} T_A &= \left|\underline{V}_{BC}\right| \cdot \left|\underline{I}_A\right| \cdot \cos\left(-\angle \underline{I}_A - \angle \underline{V}_{BC}\right) \\ T_B &= \left|\underline{V}_{CA}\right| \cdot \left|\underline{I}_B\right| \cdot \cos\left(-\angle \underline{I}_B - \angle \underline{V}_{CA}\right) \\ T_C &= \left|\underline{V}_{AB}\right| \cdot \left|\underline{I}_C\right| \cdot \cos\left(-\angle \underline{I}_C - \angle \underline{V}_{AB}\right) \end{aligned} \tag{4}$$

Where $\underline{V}_{BC} = \underline{V}_C - \underline{V}_B$, $\underline{V}_{CA} = \underline{V}_A - \underline{V}_C$ and $\underline{V}_{AB} = \underline{V}_B - \underline{V}_A$.

TABLE 2, Sequence Polarization

Operating quantity	Polarizing quantity
$3\cdot\underline{I}_1\cdot(1\angle\underline{Z}_{L1})$	$3\cdot\underline{V}_1$
$3\cdot\underline{I}_2\cdot(1\angle\underline{Z}_{L1})$	$3\cdot\underline{V}_2$
$3\cdot\underline{I}_0\cdot(1\angle\underline{Z}_{L0})$	$3\cdot\underline{V}_0$

Here, the directional decision is given by:

$$T_{32P} = |3\cdot \underline{V}_1| \cdot |3\cdot \underline{I}_1| \cdot \cos(\angle 3\cdot \underline{V}_1 - (\angle 3\cdot \underline{I}_1 + \angle \underline{Z}_{L1}))$$
$$T_{32Q} = |3\cdot \underline{V}_2| \cdot |3\cdot \underline{I}_2| \cdot \cos(\angle -3\cdot \underline{V}_2 - (\angle 3\cdot \underline{I}_2 + \angle \underline{Z}_{L1}))$$
$$T_{32V} = |3\cdot \underline{V}_0| \cdot |3\cdot \underline{I}_0| \cdot \cos(\angle -3\cdot \underline{V}_0 - (\angle 3\cdot \underline{I}_0 + \angle \underline{Z}_{L0})) \quad (5)$$

The use of the polarization methods has been described in [51] in a full FPI implementation. Note that in Eqs. (4) and (5), the impedance terms can be replaced by a customized angle, so that the directional detection capabilities can be improved in case of high impedance faults. Typical adjustments of the angle relationship between voltage and current in the quadrature polarization are 30 or 60° [52].

As shown above, the polarization method is defined for steady-state magnitudes. However, in order to coordinate the FPI with the main feeder protections, the FPI has to detect the fault direction in a very short time frame, below the tripping time of the circuit breaker. Hence, the steady-state condition may not be reached. In this case, the direction must be detected with the transient measurements.

Several methods have been proposed to tackle the problem of fast fault detection, not only for fault detection, but also for distance estimation. The Differential Equations Algorithm has been applied to many of these problems in [53]. The decomposition of the waveform in harmonic components has been proposed in [54], applying similar polarization principles to the higher order harmonics that are present in the transient state. Another approach is based on the calculation of the instantaneous active power to determine the direction of the fault. In [55], this principle has been applied to the homopolar measurements, similarly to the polarization principle T_{32V}, in Eq. (5):

$$Direction = sign\{i_0 \cdot u_0\} \quad (6)$$

In [56], the Hilbert-transformation has been applied to the homopolar current and voltage measurements to determine the direction of high impedance, transient faults. Towards the deployment of a directional FPI solution in the MV distribution grid, measuring the voltage at each FPI location can be a drawback. There exist several solutions to measure the voltage in a cheap, scalable and geometrically compact way (given that the MV distribution cabins have limited space), for example: [57-58]. However, in the last years, a new generation of directional FPIs without voltage sensors has been developed.

A. Directional FPIs without voltage sensors

Directional FPIs that do not require voltage sensors can skip the purchase, installation and maintenance of such sensors, becoming an alternative to the full equipment FPIs. Because of the absence of a voltage measurement, the voltage polarization methods described previously cannot be used. Instead, alternative signal processing techniques that only require current inputs are developed. In [59], an exhaustive state of the art on this technology is described. These methods are briefly classified as:

<u>Polarity of the current:</u> Consider FPI-1 and FPI-2 installed on phase A and a fault that happens in between. The first half of the period of the fault current waveform will be positive on one FPI and negative on the other one [60]. By checking the change of sign, the direction can be determined.

<u>Symmetrical components ratio:</u> Consider the phase-to-ground fault scheme with symmetrical components. In such faults, the positive-, negative- and zero-sequence impedance schemes are connected in series at the fault point. The analysis of the ratio of a sequence current over another sequence current (for instance, zero-sequence over negative-sequence current) leads to determine the fault direction [61-62].

<u>Current polarization:</u> The principle of voltage polarization has been described in the previous paragraphs. However, an alternative is to use the phase currents as polarization magnitudes for the sequence magnitudes, or the other way around. This method has been described for fault detection in isolated neutral grids [63].

<u>Phase current angle shift:</u> Consider the pre-fault and the faulted current phasors. When a fault happens downstream, the angle difference between both phasors would be negative, whereas if the fault occurs upstream, the angle difference would be positive [64-65].

<u>Correlation between zero-sequence and phase currents:</u> When a phase-to-ground fault occurs, because of the distribution of the fault currents in the grid circuit, the faulty phase becomes of higher magnitude, correlated with the presence of homopolar current in downstream faults. This phenomenon has become a directional method insensitive to the back-feed current that appears in highly capacitive cables [66-67].

<u>High frequency discharge:</u> A short-circuit leads to a sudden discharge of a capacitive- inductive circuit. This results in a high-frequency current if the fault was upstream. The high-frequency of the homopolar current is detected by counting the zero-crossings of such current and also its derivative to remove the possible influence of a DC offset [68].

<u>Pseudo-homopolar current frequency signature:</u> The so-called pseudo-homopolar current is calculated from the positive sign phase currents, according to:

$$\underline{I}_{0p} = \underline{I}_A^+ + \underline{I}_B^+ + \underline{I}_C^+ \quad (7)$$

The frequency signature consists of the frequency spectrum of such signal, from which the DC, the 50 Hz and the 100 Hz components amplitude is analyzed. The method consists of a logic scheme that is able to distinguish all the fault types and the direction.

Most of the previous methods use non-conventional techniques and therefore, are difficult to set up and configure for detection purposes. In order to overcome this problem, some of these methods have been designed to be auto-adaptive [69-70], so that in practice they do not require thresholds to be defined. The other methods rely on the traditional over-current detection function.

After the fault is located and isolated, the grid can be reconfigured so that the power supply of certain substations can come from the opposite direction as the usual one. It is uncertain how the FPI can adapt to this situation, so that the “forward” and “reverse” directions are coherent with the normal power supply direction. Some manufacturers have proposed to determine the normal power supply direction as the direction of the active power direction (based on the quadrature polarization principles, for instance). This mechanism may work in most of the cases, but in presence of DG along the distribution grid, it can lead to a distorted “normal power flow direction”.

B. Fault detection

Despite the fact that the fault detection field is broader than the directional fault detection field, significant work has been done regarding the deployment of the FPI. As it has been briefly mentioned before, most of the conventional fault detection algorithms that realize the FPI are based on the steady state measurements, on the over-current detection. In its early version, the FPI was manufactured with analog electronics, designed for a specific threshold (200A, 400A, 600A...). As it has been pointed out in [21], this represented a big variety of stocks for the manufacturer and it is not flexible enough for the DNOs, who which to be able to easily configure the device. One improvement was to include the option of a manual adjustment of the over- current threshold, by means of a potentiometer.

Despite the adjustment possibility, the mechanism of simple threshold has an inherent detection problem. As it has been mentioned in this paper, in those grids with low-impedance earthing, phase-to-ground faults can be detected by detecting phase over-current. Hence, one FPI is installed at each phase and that serves to detect all the typical fault types. This fault type is the one that produces the lowest fault current in comparison with the other fault types. During normal grid operation, the FPI is sensing the load current, whereas in fault conditions, it is expected to sense a high over-current. The potential non-detection case takes place in long feeders, where the grid impedance is high enough so that the FPI is unable to distinguish between the load current and the fault current. This mal-operation case can also take place in weak grids with a large short-circuit impedance or high-impedance faults that produce very low over-current.

A popular algorithm to overcome some of the problems of the previous paragraph is the so-called di/dt algorithm, or adaptive threshold. This algorithm is based on the rate of change of the current magnitude between pre-fault and fault state. Calculating the increment of current magnitude is similar to calculate “*how many times is the fault current higher than the pre-fault load current*” in a given time interval. This algorithm is implemented digitally or analog in many commercial available FPIs [71]. Still, with the di/dt algorithm, FPIs may not be able to detect most of the high-impedance (HiZ) faults. This issue hast has become a new field of research. For this reason, most DNOs establish some requirements on the minimum earth fault resistance that the FPI must be able to detect, which is normally around 2-3 kOhms.

Over the last couple years, there has been an increasing interest in transient fault detection methods, not just for the directional case, as in the previous section. This has led to the application of other mathematical techniques for that purpose, such as the wavelet functions family [72-74], the S-transform [75], the classical travelling waves theory [76-77], or a probabilistic approach to the fault detection [78], amongst many other. In case of transient faults, it is not clear what the response of the circuit breaker should be. The protective relays do not trip until the fault becomes permanent.

VI. CONCLUSION

This paper describes several approaches and improvements to the well-established FPI technology. Some of them were given in by the study of the business case considering the associated costs, such as purchase, installation, supply interruption or external factors, such as the penetration of Distributed Generation. Most of the improvements have been found in academic literature, industrial patent documents, and manufacturer catalogues. While not all the proposed improvements become commercial FPIs, they aim to provide a cost-effective solution to improve grid reliability.

Other improvements on the FPI technology have been found to be related to other research fields, such as (directional) fault detection, related to protective relays, powering the FPI, or related to electronics. After the analysis, some challenges are posed, such as how to achieve self-configuration of FPIs, how to coordinate directionality of FPIs with grid reconfiguration actions, or how to tune FPIs that work with unconventional signal processing techniques. . Clearly, there is much room for further work on the topic of fault detection and localization.

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